Behavior of a Charged Two-Level Fluctuator in an Al-AlO$_x$-Al Single-Electron Transistor in the Normal and Superconducting State

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***Abstract*-We have studied the behavior of a charged two-level fluctuator in an Al-AlO$_x$-Al single-electron transistor (SET) in the normal state over a temperature range from 85 mK to 3 K. The fluctuator caused the SET's island charge to shift by $\Delta Q_o = 0.1 \pm 0.025\, e$ with an escape rate out of each state which was periodic in the gate voltage. We compare our results to a model which assumes the fluctuator resides in one of the tunnel junctions and discuss model predictions for when the device is in the superconducting state.**

I. Introduction

Intrinsic charge noise in single-electron transistors (SETs) [1]-[3] seriously limits the possible use of these devices in applications [4]-[6]. While it is clear that the noise is caused by the movement of charges near the SET, it is unclear where the charges are located and whether they are moving ions or electrons. One way to answer these questions is by studying the behavior of a single two-level fluctuator, which produces abrupt charge shifts in the device characteristics (see Fig. 1).

Microscopically, a charged two-level fluctuator (TLF) involves a charge moving back and forth between two states which are separated by an energy barrier. The escape rates $1/\tau_1$ and $1/\tau_2$ out of states 1 and 2 will, in general, depend on the gate voltage V_g, the bias voltage V_b and the bath temperature T. In addition, one might expect that the rate could depend on other details, such as whether the SET is normal or superconducting.

By understanding these dependences, one can begin to understand the nature of the fluctuator and its dynamics. Unfortunately, while charge noise is ubiquitous in SETs and abrupt shifts in the $I - V_g$ characteristics are quite common at temperatures $T > 1$ K, clear, prominent TLFs are relatively rare. In fact, we have found only one device which exhibited a single, clear TLF over a wide temperature range (85 mK to 3 K). In this paper, we report on the behavior of $1/\tau_1$ and $1/\tau_2$ of this fluctuator as a function of V_g, V_b, and T. We compare our data to a model which assumes the fluctuator is located in one of the tunnel junctions and undergoes inelastic scattering with phonons and transport electrons. Using the parameters from the normal state data, we predict the behavior in the superconducting state.

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II. Experimental Procedure

We used standard e-beam lithography and double-angle evaporation [7] to fabricate our Al-AlO$_x$-Al SETs. From the measured characteristics in the normal state, we were able to determine the parameters of the SET: tunnel junction capacitances $C_1 = C_2 \simeq 62$ aF, gate capacitance $C_g \simeq 1.85$ aF, and junction resistances $R_1 = R_2 \simeq 315\ k\Omega$ [8].

The two-level fluctuator was characterized by fixing V_b, V_g, and T and determining the escape rate out of each state by analyzing current (I) fluctuations as a function of time. We applied a 0.5 T field to drive the SET normal. We note that because of the limited bandwidth of our system, we were unable to measure rates much greater than 1 kHz, limiting the maximum temperature to about 3 K.

III. Main Experimental Results

The dependence of the measured escape rates $1/\tau_1$ and $1/\tau_2$ versus temperature T, gate voltage V_g, and bias voltage V_b are shown in Figs. 2-4, respectively [9]. There are several features in the data which deserve comment. First, in Fig. 2, $1/\tau_1$ and $1/\tau_2$ increase with temperature T as one would expect. However, in the low-temperature limit, the rates become independent of temperature. Second, the measured rates $1/\tau_1$ and $1/\tau_2$ depend periodically on V_g with period e/C_g [see Fig. 3(a)]. Third, the measured rate $1/\tau_1$ increases for both increasingly positive and negative voltages V_b (see Fig. 4). We note that the last feature is inconsistent with barrier tilting.

The fact that the rates saturate at low temperatures suggests the TLF in not in thermal equilibrium with the bath. In particular, the ratio τ_2/τ_1 does not obey Boltzmann statistics, i. e. $\tau_2/\tau_1 \neq (n_2/n_1)\exp(-\Delta E/(k_b T))$ where ΔE is the energy difference between state 2 and state 1 and n_i is the degeneracy of state i. One mechanism which can explain this unusual feature in the data

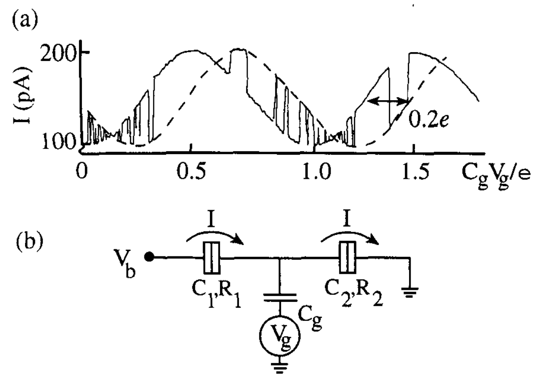

FIG. 1. (a) I-V_g characteristic of an Al-AlO_x-Al SET with a charged two-level fluctuator. As V_g is swept, the SET switches abruptly between two states. In this case, the island charge shifts by 0.2 e. (b) SET schematic. The ultra-small Al–AlO_x–Al tunnel junctions are represented by the boxes. The junctions are characterized by capacitances C_1 and C_2, which separate the leads from the island, and tunnel junction resistances R_1 and R_2.

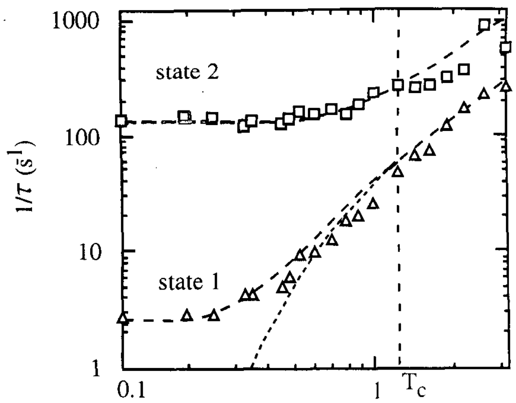

FIG. 2. Open points show measured rates $1/\tau_1$ and $1/\tau_2$ versus T. The dashed lines are results from the model when the SET is driven normal and the dotted lines are predictions from the model when the SET is operating in the superconducting state. $1/\tau_1$ and $1/\tau_2$ correspond to $\triangle$ and $\square$, respectively, and were taken with the bias and gate voltages set to $V_b = 1.2$ mV and $V_g = 0.8\ e/C_g$. We note that the normal state model includes island self-heating, while the model when the SET is superconducting assumes the island temperature equals the bath temperature.

is inelastic scattering between the fluctuator and conduction electrons flowing through the SET. If some of the electrons which contribute to the current I flowing through the SET inelastically scatter off the fluctuator, this could cause the fluctuator to switch states. This process could be active even at low temperatures because the electrons can pick up energy eV_b from the bias voltage. We note that this process could only happen if the defect resides in one of the tunnel junctions.

The periodic behavior of $1/\tau_1$ and $1/\tau_2$ is also consistent with inelastic scattering [see Fig. 3(a)]. If a fraction of the transport electrons are scattering off the fluctuator, then one naively expects $1/\tau_1$ and $1/\tau_2$ to scale with the current I flowing through the SET. Since I is periodic with V_g with period e/C_g, the rates $1/\tau_1$ and $1/\tau_2$ ought to be as well. Finally, the non-monotonic behavior of $1/\tau_1$ with bias voltage is also consistent with inelastic scattering because the current I flowing through the SET increases as $|V_b| \to \infty$.

Besides incorporating inelastic scattering, we also find that we need to include quantum tunneling to understand the qualitative behavior of the rates. The fact that $1/\tau_2 > 1/\tau_1$ for all biases suggests that state 2 is the higher energy state. Therefore, in principle, the fluctuator can switch from state 2 to state 1 by direct quantum tunneling. This process can account for the fact that we see that $1/\tau_2$ never drops below 130 s^{-1}, even when $V_b \to 0$, suggesting this is the limiting quantum tunneling rate.

IV. Models of Two-Level Fluctuators

To test these ideas, we first constructed a model in the normal state. The model assumes the fluctuator is a charged particle moving in an asymmetric, double-well potential (see Fig. 4 inset). If the particle is in the higher energy well (state 2), it can switch wells by either directly tunneling through the barrier, or tunnel after it inelastically scatters with the transport electrons or absorbs a phonon. When the particle interacts with an electron or phonon, it absorbs energy ε_2. When the particle is in the lower energy well (state 1), it can absorb a phonon and switch to state 2 directly, or it can absorb energy ε_1 by inelastically scattering with the transport electrons or absorbing a phonon, and then tunnel. The dashed lines in Figs. 2-4 show the results of the model which yield the best χ^2–fit to the data when the SET is normal [9]. We note that the qualitative agreement is good, although there are significant quantitative disagreements.

It is interesting to extend these ideas to the case when the SET is operating in the superconducting state. We first consider the inelastic scattering rate between the defect and the transport electrons. Suppose the charge is in state 2. If a quasi-particle in state $\mathbf{k}$ tunnels from the lead to state $\mathbf{k}'$ on the island, depositing an excitation energy ε_2 to the fluctuator, then the inelastic scattering rate in the superconducting state becomes [10]:

$$\Gamma_2^{in} = \frac{M_2}{e^2R_1}\int dE_k dE_{k'}\frac{|E_k|}{\sqrt{E_k^2-\Delta(T)^2}}\frac{|E_{k'}|}{\sqrt{E_{k'}^2-\Delta(T)^2}} \times f(E_k)(1-f(E_{k'}))\delta(E_k-E_{k'}-\Delta E_c-\varepsilon_2), \tag{1}$$

where M_2 is a constant proportional to the defect scattering cross-section, $f(E)$ is the Fermi-Dirac distribution, $\Delta(T) = 0.194(1-T/1.24\ \mathrm{K})^{1/2}$ meV [11] is the gap energy, ΔE_c is the junction charging energy associated with the particular tunneling process [12], and ε_2 is the energy

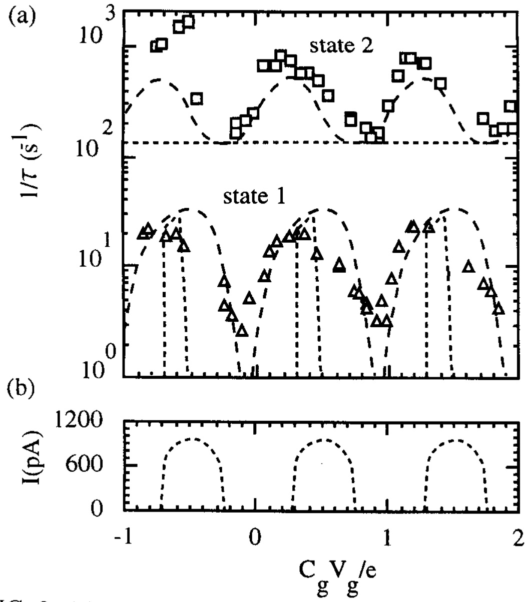

FIG. 3. (a) The rates $1/\tau_1$ and $1/\tau_2$ versus V_g. $1/\tau_1$ and $1/\tau_2$ correspond to $\triangle$ and $\square$, respectively. The data were taken with $V_b = 1.3$ meV and $T = 0.134$ K. The dashed lines are results from the model when the SET is driven normal and the dotted lines are predictions from the model when the SET is operating in the superconducting state. (b) Simulation of $I - V_g$ characteristic when $T = 0.1$ K and $V_b = 1.3$ mV.

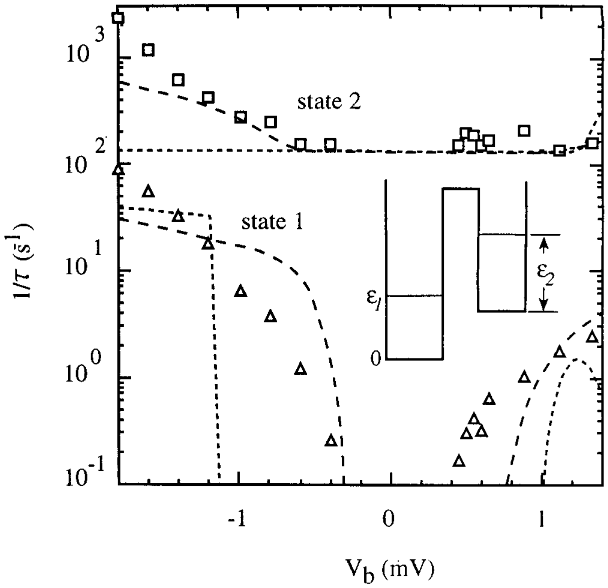

FIG. 4. The rates $1/\tau_1$ and $1/\tau_2$ versus V_b. $1/\tau_1$ and $1/\tau_2$ correspond to $\triangle$ and $\square$, respectively. The gate voltage was fixed over a range of $V_g = 0.2\ e/C_g$ to $0.4\ e/C_g$ and the temperature was fixed at $T = 0.09$ K when $V_b < 0$. When $V_b > 0$, the gate voltage was set between $V_g = 0.3\ e/C_g$ and $0.4e/C_g$, and $T = 0.13$ K. The dashed lines are results from the model when the SET is driven normal and the dotted lines are predictions from the model when the SET is operating in the superconducting state. Inset: Schematic of double-well potential. The excited states of state 1 and 2 are given by ε_1 and ε_2, respectively.

needed to excite the fluctuator. Here, we neglect island self-heating effects, and assume that the island and lead temperature are equal to the bath temperature T [13].

In the model, we assume the escape rate $1/\tau_i$ out of state i where $i = 1$ or 2 can be calculated as follows:

$$\frac{1}{\tau_i} = \sum_{n=-\infty}^{\infty} \frac{1}{\tau_i(n)} P(n), \tag{2}$$

where $P(n)$ is the probability that the SET island has n excess electrons and $1/\tau_i(n)$ is the escape rate out of state i when the island has n excess electrons. We use the Orthodox Theory in the superconducting state [14] to determine $P(n)$ for our given bias conditions V_g, V_b, and T. The rate $1/\tau_i(n)$ is determined by calculating the individual escape rates (i. e. transport electron inelastic scattering, single–phonon scattering, quantum tunneling) and then solving the master equation for this system.

The dotted lines in Figs. 2-4 show the results of the model when the SET is in the superconducting state. For the superconducting state, we use the same model parameters found from the best fit in the normal state.

The predictions of the superconducting model differ dramatically from the predictions of the normal state model. In Fig. 2, the escape rate $1/\tau_1$ drops far below 2 s^{-1} as the temperature $T \to 0$. Also in Fig. 3(a), we see that the superconducting model predicts $1/\tau_1(V_g)$ is more sharply peaked and drops to zero whenever $V_g < 0.3$ e/C_g mod (e/C_g) and $V_g > 0.5\ e/C_g$ mod (e/C_g). Moreover, the superconducting model rate $1/\tau_2$ is independent of V_g. Finally, in Fig. 4, the superconducting model predicts that $1/\tau_1 = 0$ when $|V_b| < 1$ mV. Also, the rate $1/\tau_1$ peaks at $V_b = 1.2$ mV when $V_b > 0$ and the rate $1/\tau_2$ is independent of V_b except when $V_b > 1$ mV.

The reason the superconducting model predicts $1/\tau_1(T) \ll 1\ s^{-1}$ when T < 400 mK is because the inelastic scattering rate Γ_1^{in} drops off rapidly as $T \to 0$ when $V_g = 0.8\ e/C_g$, the experimental gate voltage value. As one can see in Fig. 3(b), no current flows through the SET when $V_g = 0.8\ e/C_g$, $V_b = 1.3$ mV, and $T = 100$ mK. Therefore, one expects $\Gamma_1^{in} = 0$ when the SET is at this temperature and bias point. In practice, to prevent $1/\tau_1(T)$ from going to zero, one needs to set V_g closer to $V_g = 0.5\ e/C_g$ where ample current is flowing through the device.

As one would expect, the model predicts a sharp rise in $1/\tau_1(V_g)$ at precisely the same gate voltage as when the current abruptly turns on [see Figs. 3(a) and 3(b)]. Surprisingly, however, the rate drops to zero when $V_g = 0.6$ e/C_g, even though current is flowing through the device. This occurs because the transport electrons need to overcome the charging energy ΔE_c [12] associated with changing the number of excess electrons on the island *and* supply energy ε_1 to the fluctuator. While there are many electrons with the necessary charging energy to cause current to flow in the SET, very few electrons also have the extra energy needed to excite the fluctuator.

We note that the sharp onset in current I at $V_g = 0.3$ e/C_g suggests that one can test whether inelastic scattering is the only mechanism significantly driving the fluctuator at low temperatures. Suppose one biases the SET very close to but less than $V_g = 0.3\ e/C_g$. If the fluctuator switches, the island charge will change by $\delta Q_o = 0.1$ e and current will flow through the device. Therefore, one can directly observe whether the fluctuator switches when no current is flowing through the device.

Finally, we note that in Fig. 4, the peak in the calculated superconducting rate $1/\tau_1$ when $V_b = 1.2$ mV is caused by barrier tilting. As V_b is increased, the depth of the well associated with state 1 increases. Consequently, if barrier tilting were the dominant effect, we expect the rate $1/\tau_1$ to decrease as V_b is increased. However, since inelastic scattering tends to increase with V_b, the overall escape rate is determined by the interaction of these two competing effects. In the normal state, Γ_1^{in} increases so strongly with V_b that it dominates over barrier tilting and $1/\tau_1(V_b)$ increases monotonically when $V_b > 0$. This is not the case in the superconducting state because the inelastic scattering rate depends weakly on V_b. Therefore, as the barrier is tilted by increasing V_b, Γ_1^{in} is not growing rapidly enough to keep $1/\tau_1(V_b)$ from peaking.

V. Conclusions

We have measured the lifetimes of the two states of a charged two-level fluctuator in a normal SET as a function of the gate voltage V_g, bias voltage V_b, and temperature T. The data is consistent with the idea of transport electrons inelastically scattering off a charged fluctuator. If there is inelastic scattering of this nature, the defect must be located in the tunnel junction. We model the superconducting state and find that it differs from the normal state. The difference arises because in the superconducting state energy is spent to create quasi-particles which tunnel and scatter with the fluctuator. The sharp features of the superconducting $I - V_g$ characteristic provide a rigorous test of whether inelastic scattering between the fluctuator and the transport electrons is the dominant driving mechanism in the low-temperature limit. Therefore, by measuring the fluctuator when the SET is superconducting, one can further explore the ultimate source of charged fluctuations in SETs.

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[9] The normal state data is also presented in M. Kenyon, Jonathan L. Cobb, A. Amar, D. Song, C. J. Lobb, F. C. Wellstood, and Neil M. Zimmerman, "Dynamics of a charge fluctuator in an Al-AlO_x-Al single–electron transistor," submitted to *Phys. Rev. B* July 30, 1998. Details of the normal state model are also discussed in this paper.

[10] The rate Γ_1^{in} is similar to Γ_2^{in}. We write it as:

$$\Gamma_1^{in} = \frac{M_1}{e^2 R_1} \int dE_k dE_{k'} \frac{|E_k|}{\sqrt{E_k^2 - \Delta(T)^2}} \frac{|E_{k'}|}{\sqrt{E_{k'}^2 - \Delta(T)^2}} \times f(E_k)(1 - f(E_{k'}))\delta(E_k - E_{k'} - \Delta E_c - \varepsilon_1). \tag{3}$$

M_1 is an overall scaling factor, proportional to the cross-section and ε_1 is the energy need to excite the fluctuator when it is in state 1. The other terms in this equation are explained in the discussion following Eq. (1).

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